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ADVANCING COASTAL CLIMATE ADAPTATION IN DENMARK BY LAND SUBSIDENCE MAPPING USING SENTINEL-1 SATELLITE IMAGERY

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There are still large uncertainties in projections of climate change and sea level rise. Here, land subsidence is an additional factor that may adversely affect the vulnerability towards floods in low-lying coastal communities. The presented study performs an initial assessment of subsidence mapping using Sentinel-1 satellite imagery and leveling at two coastal locations in Denmark. Within both investigated areas current subsidence rates of 5-10 millimeters per year are found. This subsidence is related to the local geology, and challenges and potentials in bringing land subsidence mapping and geology into climate adaptation are discussed in relation to perspectives of a national subsidence monitoring system partly based on the findings from the two coastal locations. The current lack of subsidence data and a fragmentation of geotechnical information are considered as hindrances to optimal adaptation in Denmark. A simple decision support system is suggested to gradually implement subsidence monitoring and to include geotechnical information in coastal climate adaptation to the benefit of municipalities and other stakeholders.

Keywords: Land subsidence, geotechnical archives, geological models, Sentinel-1, coastal climate impacts, decision support, adaptation, precision leveling

Climate change adversely impacts society and adaptation is a global challenge faced by all with both local and international dimensions (UNFCC 2016). The vulnerability and impacts from floods and inundation along many coasts are exacerbated by sea level rise, more extreme sea levels, and a potential increase in the frequency and intensity of storms (IPCC 2013; IPCC 2014; Wong et al, 2014). Regional variations from the global relative mean sea level rise e.g., due to ocean circulation patterns, interannual and decadal variability (e.g. Zhang et al, 2012), glacial isostatic adjustment (e.g. Peltier et al, 2015), and the proximity to melting icecaps (e.g. Gomez et al, 2010) scope many regional sea level model studies (e.g. Slangen et al, 2016). Still, large uncertainties in the sea level rise expected in this century (Grinsted et al, 2015; Jevrejeva et al, 2014) implicate regional coastal impacts and levels of adaptation required (Dronkers and Stojanovic, 2016). Furthermore, natural or human-induced land subsidence must be accounted for locally (Nicholls, 1995) to evaluate the potential extent and depth of future floods from storm surges and extreme precipitation events (Vognsen et al, 2013; Sorensen et al, 2016). Relative sea level changes are relevant in climate impact studies, and even a few millimeters of land subsidence a year will exacerbate the current global mean rate of sea level rise of c. 3.4 mm/y (Nerem et al, 2010; http://sealevel.colorado.edu/) significantly in terms of vulnerability to floods.

Whereas land subsidence, due e.g. to gas or groundwater extraction, has been investigated and related to coastal floods abroad, little attention has been given to this issue in Denmark. There are two main reasons for this: first, subsidence has not been considered a challenge and, secondly, there is a general lack of data on height variations in terms of repeated measurements to well-established points of reference. However, Broge et al (2013) found the most low-lying Danish areas to be also the most susceptible to subsidence from a screening of existing leveling data, and the authors ascribed this to soil and groundwater processes in landfills and soft sediments. Coastal towns and communities may thus become more vulnerable to floods than anticipated from sea level rise alone, and ongoing or future land subsidence should be accounted for in climate adaptation in Denmark, too. This will, at the least, serve the purpose to limit uncertainties of climate impacts. This is particularly relevant as the ten largest Danish cities are located by the coast and 80% of the population lives less than three kilometers from the ocean. Also, many towns are of medieval origin and have long storm surge records (Piontkowitz and Sorensen 2011).

Objectives of this paper are to make an initial assessment of Sentinel-1 satellite imagery for subsidence mapping in Denmark and to compare this with leveling data at two coastal locations. In addition, geological information from the two locations are collected, interpreted, and related to the subsidence data. Based on this, the use of information on land subsidence and geology is discussed in relation to climate adaptation and, furthermore, perspectives of a national subsidence monitoring system partly based on the findings from the two coastal locations are discussed.

DATA AND METHODS

Following a presentation of the two study locations, methods for subsidence monitoring and geological model preparation are presented together with an overview of data used.

Study locations

Denmark borders the North Sea and the Baltic Sea (see Figure 1), and the Danish landscapes are predominantly a product of the Quaternary Fennoscandian glaciations with glacial tills and meltwater deposits; postglacial Aeolian, freshwater, and marine deposits (Pedersen et al, 2011). The Pre-Quaternary surface is found at varying depths (Binzer and Stockmarr, 1994).

The two study locations 'Thyboron' and 'Aarhus' (see Figure 1b and Figure 1c) have been selected based on an initial suspicion of ongoing land subsidence and from the fact, that both areas become increasingly susceptible to floods from storm surges with sea level rise. Leveling data collected from two or more campaigns over the locations exist to gain knowledge about recent

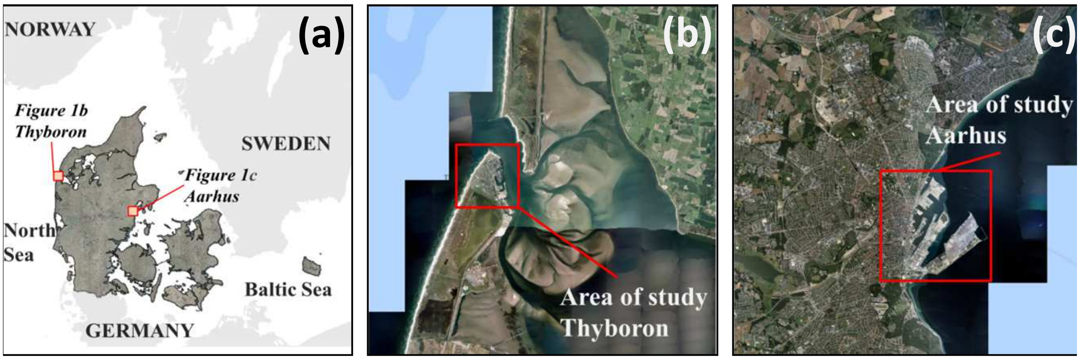

Figure 1. Map of Denmark (a) with the Thyboron (b) and Aarhus (c) study locations indicated.

elevation changes and to compare this with satellite-based results. 'Thyboron' is a fishing town located on a sandy barrier towards the highly energetic North Sea coast. Protected by large sea dikes towards the North Sea, the town is currently most vulnerable to floods from the adjacent Limfjord due to a land elevation of only 1.0-2.5 m DVR90 (Danish datum approximately equivalent to mean sea level in 1990). Rapid urbanization has occurred on reclaimed areas on the former fjord bottom since the 1960s in a direction from north to south (Sorensen et al, 2016). The 'Aarhus' study location contains quays and breakwaters. The Aarhus breakwater construction was carried out over a ten-year period starting around the turn of the millennium, and the filling of the area behind was performed from west to east to an approximate level of 2.0 m DVR90. Current 100 year extreme return water levels from storm surges are respectively 1.93 m DVR90 for Thyboron Harbor and 1.64 m DVR90 for Aarhus Harbor (Sorensen et al, 2013).

Measuring land subsidence

Data from the Sentinel-1a satellite are provided free of charge by the European Space Agency (esa.int) and via the European Earth Observation Program, Copernicus (copernicus.eu). This is coordinated and managed by the European Commission (ec.europa.eu). The satellite has been operational since 2014. In order to become useful for e.g., subsidence studies, sequences of Sentinel-1 data from repeated imagery over an area needs to be processed (ESA, 2016). For the presented study, the image processing has been carried out by NORUT, NGU, and PPO.Labs (Larsen et al, 2006; Levinsen et al, 2016; Marinkovic et al, 2016). The data processing is performed using Persistent Scatterer Interferometry (PS-InSAR) (Ferretti et al, 2001; Ferretti et al, 2007). Basically, this means that each time the satellite passes over an area, a satellite radar signal is reflected on the ground and the return signal is measured. From the phase shift in the signal as a measure of time of travel, the distance between the satellite and the ground reflection point (PSI-point) is derived. In order for the radar signal to be reflected there must be natural reflection points on the ground like house corners or other constructions. As the spatial resolution of the Sentinel-1 image is 5*20 meters, this also means that each discrete point in the results may represent one or more reflection points within this area. Over time, and as the number of images in 'the stack' over an area increases, the coherence between individual points in the images may be used as a quality measure. Here, 27 images acquired in the period March 2015 – March 2016 over each of the two study locations have been used to infer average rates of vertical land movement. The short time series of images do not allow for any detailed interpretation of the averaged vertical land motion at individual PSI-points or of variations in subsidence over time, but results may reveal patterns of variation detected over Thyboron and Aarhus. Furthermore,

Data Source	Location	
	Thyboron	Aarhus
Sentinel-1A satellite	Mode: Interferometric Wide Swath Data period: 03/2015 – 03/2016 Track: 139 Burst: 20330 No. of images: 27 Satellite repeat cycle (days): 12 Image resolution (m): 5*20	Mode: Interferometric Wide Swath Data period: 03/2015 – 03/2016 Track: 139 Burst: 20366 No. of images: 27 Satellite repeat cycle (days): 12 Image resolution (m): 5*20
ERS2 satellite	Mode: Synthetic Aperture Radar Image Data period: 1995-2001 Track: 108 Frame: 2457 No. of images: 48 Satellite repeat cycle (days): 35 Image resolution (m): 5*25 (ESA Project, Id. 30907).	n/a
Precision leveling	Years: 2006, 2009, 2012, 2015 No. of benchmarks: 50 Reference: DK datum network	Year: 2012, 2015 No. of benchmarks: 145 Reference: Local

Table 1. Specification of data used for measurements of vertical land movement.

the rate at the individual PSI-points will be relative to one PSI-point of defined zero movement over each area. Finally, rates are given as a vertical 'line-of-sight' (LOS) displacement based on the angle of incidence of the satellite's radar signal. This angle is approximately 40 degrees for Sentienl-1, and must be multiplied by 1.3 to yield vertical rates of movement. Considering the short time series and the abovementioned limitation in interpretation, the results are not resolved into vertical and lateral changes over the period investigated. The relative uncertainty in subsidence rates are believed to be 'a few millimeters'. Over time and as longer time series of images become available, sub-millimeter accuracy may be anticipated in subsidence mapping based on Sentinel-1 data. Table 1 provides information about data used over the study locations.

In addition, images over Thyboron have been acquired from the ERS-2 satellite in the period 1995-2001 and thus prior to the quays and breakwater constructions at Aarhus. These images have been processed separately also by means of PS-InSAR methods as previously reported by Sorensen et al (2016). As ERS-2 and Sentinel-1 data are referenced to different reflection points, results are not directly comparable. Details of data images and acquisition are given in Table 1.

Based on the initial suspicion of land subsidence, approximately 50 new height reference points were established in Thyboron in 2006. Subsequently, precise leveling campaigns have been carried out in respectively 2006, 2009, 2012, and 2015 and related to assumedly stable reference points in the Danish datum leveling network. Over this period, linear trends are imposed on the data to obtain rates of vertical land deformation (Sorensen et al, 2016; Vognsen et al, 2013). At the Aarhus study location a number of height benchmarks were established in 2012 and were consequently leveled in August 2012 and August 2015 for the purpose of this study. Despite consisting of only two campaigns, rates of subsidence have been calculated relative to three benchmarks at the western edge of the Aarhus study location which shows no internal variation in heights between the campaigns and are assumed to be stable. The leveling campaigns at both locations were carried out by the Agency for

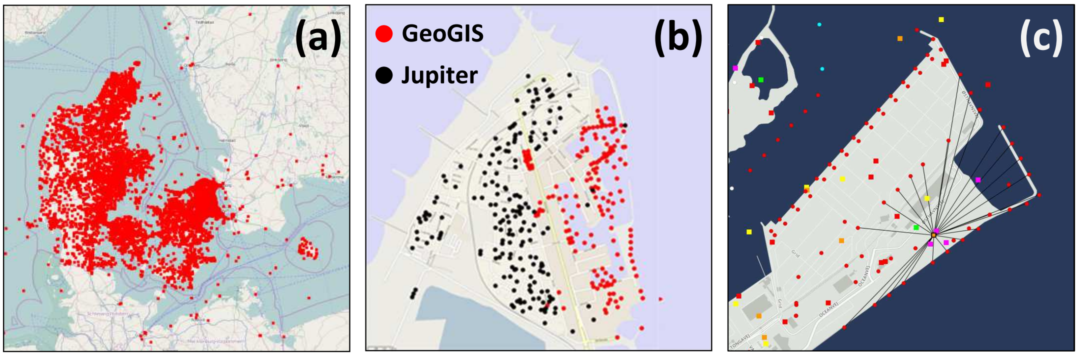

Figure 2. Projects included in the GeoAtlas database (a); availability of geological and geotechnical data over Thyboron (b), and available GeoAtlas data over Aarhus showing that a single project may contain many wells (black lines) (c).

Data Supply and Efficiency (sdfe.dk, formerly known as the Danish Geodata agency) which is also in charge of maintaining the national leveling network.

Compiling geological information

Geotechnical and geological surveys in Denmark have been performed by private consulting companies, public authorities, and universities. Knowledge about subsurface geology is important in construction works, where contractors require information about site-specific geotechnical properties. In general, difficult subsurface conditions increase the need of geotechnical information. Currently there is no common or shared national platform to get an overview of the total number of investigations. The national 'Jupiter' database (GEUS, 2016) contains 280,000 wells. Although many wells have little geologic or geotechnical information, the easily accessible and searchable on-line database is a useful source of information. A 'model database' hosted by the Geological Survey of Denmark and Greenland (GEUS) contains geological and hydrostratigraphic models at local, regional, and national scales produced mainly in relation to publicly funded groundwater and aquifer investigations and mapping (e.g. Ditlefsen et al, 2012). In the context of the presented work, a geological model is simply a 2-D or 3-D representation of the subsurface geology based on interpreted data. Existing models in the database do not cover the study locations, however.

In addition to Jupiter, the largest private Danish geotechnical database, GeoAtlas (2016), has +60,000 'GeoGIS' projects concentrated around towns and infrastructure. GeoAtlas contains in excess of 200,000 wells, 500,000 measurements of shear strength, and 300,000 measurements of water content, and the density of projects in Denmark and over the two study locations is sketched in Figure 2. GeoAtlas is fully digitized with searchable and georeferenced pdfs at project level. Usually each well in a GeoAtlas project is associated with geographic coordinates as well as detailed geotechnical descriptions of the subsurface geology, groundwater levels and shear strengths as mentioned above. The two databases contain information based on different primary tasks and sectors: Jupiter is to a large extent based on and extended by public investigations related to groundwater and the environment and to research, whereas GeoAtlas projects have a more industrial scope related to construction works in the private sector. A combination of the two databases often provides data with a high spatial coverage. Various other companies hold geotechnical projects which have not been included in the presented work.

The available geotechnical information over Thyboron and Aarhus has been digitized by the authors to produce 3-D geological models. For Aarhus, the collection of data has been made

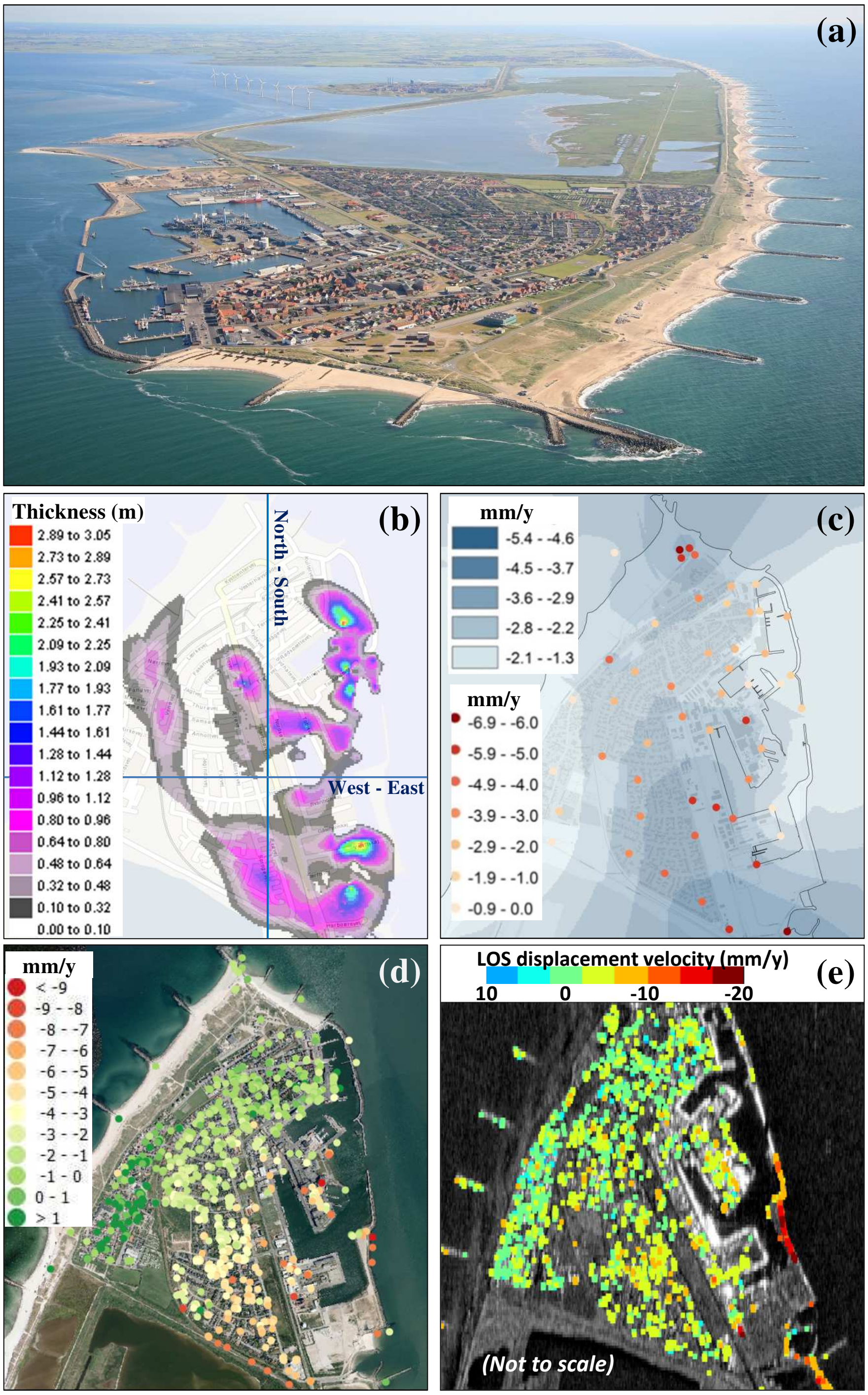

Figure 3. Thyboron: photo towards south (by courtesy of Hunderup Aerial Photography/Danish Coastal Authority)(a); isopach map of gyttja/soft sediments (b); measured and interpolated vertical rates of land movement (subsidence is negative) from precision leveling (2006-2015) (c); measured rates from ERS2 (1995-2001) satellite imagery (d), and measured 'line-of-sight' (LOS) rates from Sentinel-1(2015-2016) satellite imagery (e).

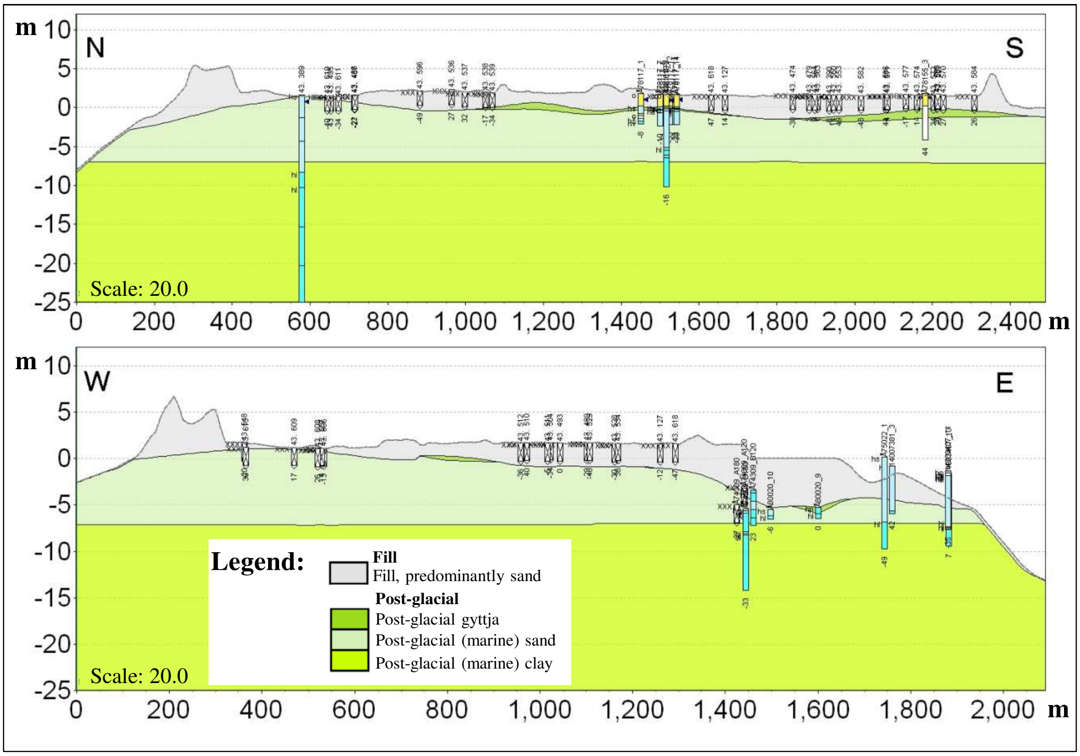

Figure 4. Geological profiles from Thyboron in North-South and West-East directions based on a 3-D geological model from digitized geotechnical archive information (positions of profile lines are shown in Figure 3b).

previous to and during the construction work. For Thyboron, many of the wells date back to the 1950's and before. Here, all geological information from the +200 wells has been transferred from the old analog reports to a digital form. Consequently, spatial interpretations of the geology have been made using the GEOScene3D.com software, which is an integrated 3-D geological modeling software.Depending on the density of wells, this interpretation contains uncertainties regarding the lateral extent and thicknesses of subsurface layers. Over Thyboron, Jupiter data mainly cover the residential western part of the town and GeoAtlas data cover the port and industrial areas. Some geotechnical information, e.g., later removal of material for port basin construction, is not representative of the present geology but may still support subsurface interpretation in the geological model.

RESULTS

As seen in Figure 4, the geological model of Thyboron shows Holocene marine clays ('Agger Clay') at depths of 6-30 m (positions of N-S and W-E profiles are shown in Figure 3b). Above this layer are marine sands as well as layers and lenses of gyttja/soft sediments. Geotechnical investigations do not entirely cover Thyboron, but the isopach map of soft sediments seen in Figure 3b indicates increasing thicknesses towards south and east. Above the gyttja layer is approximately 2-4 m of fill material including artificially created or stabilized dunes towards north and west. The relative subsidence patterns from precise leveling 2006-2015 seen in Figure 3c, and from ERS-2 imagery 1995-2001 in Figure 3d (both figures are adapted from Sorensen et al, 2016) show a good agreement to indicate net subsidence rates of 5-7 mm/y towards SE and more stable conditions towards west. Sentinel-1 results (2015-2016) indicate the

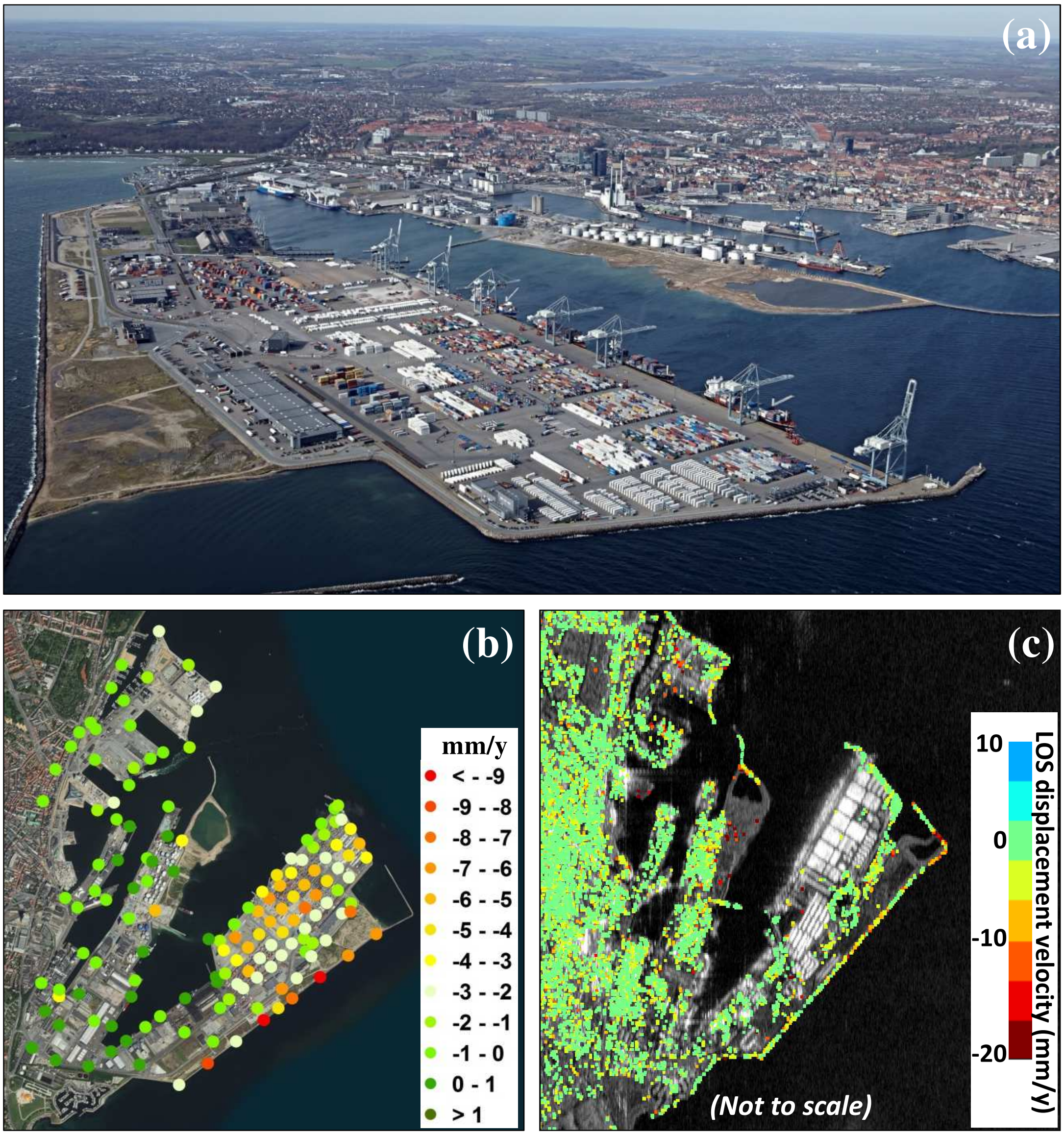

Figure 5. Aarhus: photo of Aarhus East Harbor towards SW with the city of Aarhus in the background (by courtesy of Mr. Joergen Weber and Port of Aarhus) (a); measured vertical rates of land movement (subsidence is negative) from precision leveling (2012-2015) (b); and measured 'line-of-sight' (LOS) rates from Sentinel-1 (2015-2016) satellite imagery (c).

same geographical pattern of relative vertical displacement rates. In addition, the subsidence of the recently constructed or renovated eastern harbor breakwaters is significant as shown in Figure 3e based on the radar geometry (yielding a different scale of the map compared to the georeferenced leveling and ERS-2 GIS-maps). From a visual inspection, subsidence rates exceeding 5 mm/y are thus generally found in the areas with thick layers of soft sediments. Although additional causes of subsidence may prevail, the ongoing subsidence seems related to the thickness of soft sediments and to the thickness and time of landfill. Subsidence rates may decline over time, but a more detailed evaluation of this has not been performed within the presented study.

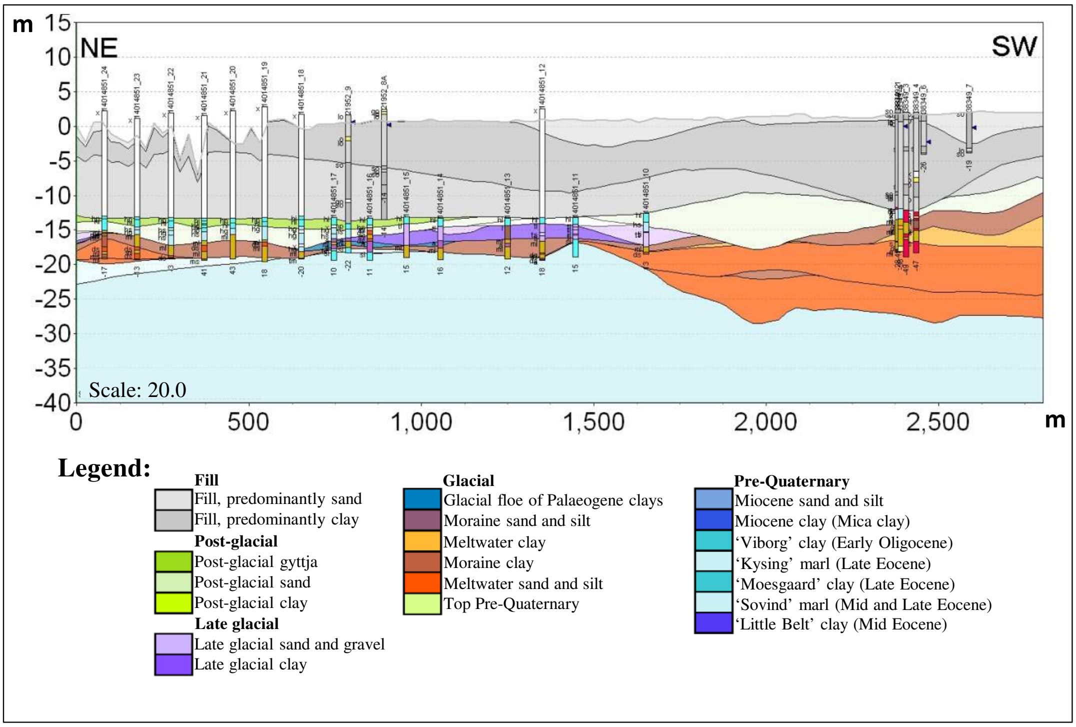

Figure 6. Geological profile in a 2,800 m (NE-SW) transect along the eastern breakwater of Aarhus East Harbor based on a 3-D geological model from digitized geotechnical archive information (not all legend types are present in the profile).

At Aarhus, the Sentinel-1 results shown in Figure 5c reveal significant relative subsidence along the outer southeast breakwater. A visual inspection unveil the fact that the inferred subsidence from Sentinel-1 data shows good spatial correlation to the subsidence rates of benchmarks measured from precision leveling in 2012 and 2015. Over this period, as seen in Figure 5b, subsidence rates of 3-10 mm/y were recorded along the entire breakwater except in a few "hot spots" with a much larger subsidence. The southern third of the breakwater is located at about 10 m water depth and is based on deposits of postglacial sand and glacial or late glacial clays and sands as shown in the 2-D geological model profile in Figure 6. However, at level -30 m these relatively competent deposits are underlain by Palaeogene clay of extreme plasticity (Okkels et al, 2011) with relatively poor soil properties to a great depth. The northern two thirds of the breakwater with the largest subsidence rates cf. Sentinel-1 is located at a depth of approximately 13 m after replacement of a 1-2 m thick and highly compressible post-glacial top layer (gyttja and soft organic clays) with sand fill. The fill is based on approximately 5 m of deposits consisting of postglacial sand and late glacial and glacial sands and clays with embedded glacial floes of high plasticity Palaeogene clays. From elevation -20 m, i.e., about 10 m higher than below the southern part of the breakwater, the predominantly competent deposits are underlain by Palaeogene clay as well.

The breakwater filling consists of competent materials of sand, gravel, stone and blocks and the subsidence in the filling itself is small and insignificant. By contrast, the weight of the breakwater and the subsequent filling for the harbor behind the breakwater has resulted in load-dependent subsidence of the breakwater from consolidation and subsurface creep. This subsidence is ongoing and will continue for a long time, although presumably at a diminishing rate. In the northeastern part of the breakwater, where the filling is largest and the Palaeogene clay is situated at the shallowest depth, the risk of subsidence "hot spots" is largest. This is most likely caused by either consolidation or unsatisfactory stability conditions due to embedded glacial floes of Palaeogene clays in the Quaternary strata, or, soft sediments left below the filling. Furthermore, current subsidence rates reflect that the filling for the breakwater and the reclaimed land behind is performed over a ten year period.

DISCUSSIONS

The discussion is divided into three parts. Firstly, results on geology and subsidence are discussed. Secondly, the relevance of bringing in such information in climate adaptation in Denmark is discussed, and finally perspectives for a national setup for subsidence monitoring are discussed.

Interpreting subsidence and geology interplay

The use of satellite imagery and leveling combines a 'technology now becoming mainstream' with a well-established one: leveling offers the highest precision to a very limited number of height benchmarks, whereas PS-InSAR offers many point measures at a lower precision and accuracy. Compared to these, airborne Lidar-methods produces e.g. digital elevation models (DEM's) with a very high resolution but at a comparatively lower accuracy. In order to infer subsidence rates of a few mm/y which is the focus in the presented study, current Danish DEMs do not offer an alternative to satellite measurements for subsidence mapping. Precision leveling at the investigated locations points to areas of subsidence that are also discernible in the Sentinel-1 data and exhibit similar rates of subsidence. At Thyboron, the ERS2 data show the same pattern of subsidence as the Sentinel-1 data. Due to relatively large differences in magnitude of the vertical displacement rates measured within each location, the PS-Insar method offers credible subsidence rates at a high spatial and temporal resolution despite the short data series. As such the method is superior to leveling regarding both the acquisition of data and potential repetition of calculations as more data become available. However, the calculated rates are relative and must be defined in relation to some arbitrary point in the map, which may or may not show stability in absolute terms. Small relative subsidence rates within an area are difficult to measure and interpret, i.e., it is not possible yet to identify whether an entire town is subsiding a few mm/y compared to the surrounding areas. Leveling is accurate and benchmarks are well defined and referenced. However, leveling is also laborious and benchmarks yield no information, strictly speaking, about the vertical movement of surrounding areas. In addition, repeated leveling data are rarely available for calculations of past and ongoing land subsidence. As the data from Thyboron and Aarhus show, subsidence can be inferred from leveling and referenced to a national datum system, however. As such the two methods complement each other in identifying areas of subsidence. In order to merge the two methods and to reference rates of subsidence from satellite measurements in absolute terms and with a high accuracy, it is necessary to perform detailed and repeated measurements (Karila et al, 2013). As a means to establish the connection between radar satellite results and the datum leveling network, artificial corner reflectors may be deployed (e.g. Marinkovic et al, 2007). In continuation of the presented study, such reflectors are in the progress of being deployed in Thyboron with an ambition to construct a corner reflector network over Denmark. The reflectors must be placed in areas without other constructions and act as unique identifiers in satellite images.

Compilations of recent and historic geotechnical investigations into 3-D geological models potentially allow for a spatial and depth-integrated interpretation of vertical surface changes expected or measured. When combined, the isopach map over Thyboron and the leveling, ERS-2 and

Sentinel-1 subsidence maps indicate a spatial relation between the magnitude of subsidence and thickness of soft sediments. Knowledge about subsidence rates in areas of the town with no geotechnical information may be used to make pre-assumptions about subsurface properties. Likewise, geotechnical information may be utilized to make initial assumptions about future subsidence in areas with no PSI-points, e.g., previous to urbanization. However, such relations need further exploration for Danish conditions. The connection between subsidence and geology is well-described in the literature but is new in a Danish climate adaptation context. Here, current subsidence rates may be projected into the future based on the geotechnical knowledge, and the near real-time monitoring of surface changes made possible by Sentinel-1 may enhance the consequence modeling of changes in surface run-off and groundwater management practices or make more realistic flooding scenarios, for instance.

Geological models and the utilization of satellite imagery extend the scale from construction site specific monitoring of subsidence and geotechnical investigations to larger areas typical of consideration in urban climate adaptation and in flood risk reduction schemes. The collection and digitization of geotechnical archives is costly, and the calculations based on the freely available Sentinel-1 data for subsidence mapping are by no means trivial or inexpensive. A demand for such products within industry, public administration, and/or academia must therefore be supported by use cases such as the ones presented here in order to advance their use and applicability in Denmark.

Subsidence monitoring in climate adaptation

Danish areas of land subsidence have not been systematically mapped, but subsidence is becoming recognized as a potentially significant factor in relation to flood risk reduction and climate adaptation with national (DCA, 2013; DCA, 2016 p. 38) and local authorities (e.g. Lemvig Municipality, 2014). Given the current rates of subsidence at Thyboron and Aarhus, the areas' liability to floods will increase over the coming decades even without sea level rise. Subsidence rates may be negligible in many coastal areas, whereas they may be three times larger than the rise in mean sea level in others. Subsidence should thus be considered and included in flood risk assessments, e.g. in relation to the implementation of the EU Floods Directive and in municipal adaptation plans. This accentuates the need of reliable subsidence data as pointed out by Broge et al (2013) with a focus on the urbanized, low-lying coastal areas most liable to experience subsidence. From the authors' correspondence with several municipal authorities, subsidence is suspected or is known to occur in several coastal towns in addition to Thyboron and Aarhus. However, this knowledge remains mostly "unofficial", is unquantified and is thus absent in management and planning. In order to get an overview of local area magnitudes of subsidence, it is suggested to publicly finance a first national, or, sub-national mapping using Sentinel-1 data. Based on this mapping, the current and future needs for subsidence monitoring and data services can be discussed and established between private and public sector end-users. Subsequently, subsidence maps may potentially become part of regional or national open data schemes, or, products may e.g. be purchased by individual companies or municipalities in need of updated information. In both cases, a service must be set up to deliver the calculations and maps in useful formats to the end-users.

The compilation of geotechnical archives into geological models is a huge task that involves a multitude of private and public stakeholders. So far, geotechnical and geological information relate mainly to construction works and groundwater modeling and with little attention paid to climate adaptation and flood modeling. A starting point for the use of existing and development of new geological models could be the municipal level as the municipalities possess insights about previous investigations and have the possibility to gather geotechnical information from companies and consultants. Still, the use for water-related adaptation purposes of geologic models, in relation to but not restricted to subsidence mapping, needs to be further explored by the owners of geotechnical archives, the municipalities and science.

Perspectives of end-user products

To become effective subsidence data and geologic models must be integrated for use in coastal climate adaptation at the end user level. More work is needed to develop methods for tying InSAR based land movement monitoring to precision leveling benchmarks where absolute elevation is known with the highest possible accuracy. Furthermore, there is a need to investigate how subsidence data through interpolation techniques may be enhanced by geotechnical data and vice versa. In addition, these must relate to other data and climate change indices. This includes information about projections of sea level rise, extreme precipitation, groundwater levels, surface runoff, flood risk, town planning etc. and includes also some measures of uncertainty to be accounted for. By gradually detailing the geological knowledge and being given access to monitor and project surface changes, much of the uncertainty related to future land subsidence can be eliminated. In addition, undesired subsidence effects from e.g., groundwater extraction or construction works may be dealt with or avoided. In addition to national authorities and municipal administrations within groundwater, planning, the environment, and adaptation; water and wastewater utility companies, port authorities, larger private enterprises, and consulting companies may be relevant stakeholders and users of data. The construction of a climate decision support system related to subsidence and geology must therefore be based on the diverse needs of the stakeholders and must share knowledge relevant to all of these. Also, the system must be dynamic and operational to the end users and to some extent be capable of predicting effects of system changes on future subsidence.

A subsidence map may serve as a starting point to detail the current pattern of land movement within an area. Secondly, geotechnical data may be compiled for focus areas in order to interpret the causes and magnitudes of change. Based on this, municipal decisions may be made to either mitigate or to further monitor changes and/or to collect additional geotechnical data. Larger systems' changes like constructions, groundwater withdrawal, or adaptation measures that may affect ground stability may be assessed and included in the decision support before implementation. By taking climate adaptation as a pivotal point of collaboration, this allows individual stakeholders to utilize and use data in more detail and still maintain a relatively simple shared decision support for municipal climate adaptation to be operated by non-experts, and to feed this with knowledge from the individual sectors. As a provider of geographic data - potentially including subsidence maps in the future, the Agency of Data Supply and Efficiency under the Danish Ministry of Energy, Utilities and Climate, may play an active role as the national authority guiding the use of subsidence maps and securing feed-back mechanisms between the users of the decision support system and the downstream services of the Copernicus program.

CONCLUSION

Knowledge about land subsidence and geology may advance coastal climate adaptation. Subsidence mapping from Sentinel-1 imagery and geological models based on geotechnical archives have been presented for two Danish study locations. Results point to the added value of bringing this information together in the assessment of coastal climate change impacts. The monitoring and interpretation of land subsidence processes that may affect future liability to floods is greatly improved from the inclusion of geotechnical knowledge. More interdisciplinary work is necessary to gain a deeper understanding of the connected and integrated hazards and climate change impacts in coastal areas. Still, there is no national overview of land subsidence in Denmark. This is a hindrance to the evaluation of extent and scale of subsidence and in the provision of optimal adaptation measures by affected municipalities.

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